Evaluation of Stopping Powers of Superheavy Ions with Z up to 124 in Al and U

Yong Hee Chung*

Department of Chemistry, Hallym University, Chuncheon 200-702

Abstract

Electronic and nuclear stopping powers of superheavy ions with Z up to 124 and A=300 in Al and U were estimated in the energy range of 0.01-0.20 MeV/u. The corresponding stopping powers were estimated using stopping powers of ions with $6 \leq Z \leq 92$ obtained from SRIM. The results were compared with those deduced from Northcliffe and Schilling′s stopping-power tables and with experimental data for ^{16}O and ^{19}F ions in Al. Estimated electronic stopping powers of the light ions agreed better with their experimental values above 0.10 MeV/u than the SRIM data.

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*Electronic address: yhchung@hallym.ac.kr; Fax: +82-33-256-3421

I. INTRODUCTION

In the study of the excitation function of superheavy ions their energy losses have to be known along with their masses, which can be taken from one of the mass tables [1–3]. No energy loss data are available to heavy ions with Z>103. The electronic stopping-power and range tables for ions with $1 \leq Z \leq 103$ at 38 energies ranging from 0.0125 to 12 MeV/u in 24 media have been reported by Northcliffe and Schilling [4]. Hubert *et al.* [5] reported electronic stopping-power and range tables for 2.5-500 MeV/u ions with $2 \leq Z \leq 103$ in 36 solid materials. However, nuclear stopping powers were not listed in both tables. Electronic and nuclear stopping powers of ions with $Z \leq 92$ in various media can be obtained from SRIM [6], but stopping powers of charged particles with Z>92 are not available. There are scarce experimental data and expected values of stopping powers for heavy ions with Z>103, but the stopping power of ^{289}Fl (Z=114) in Mylar was reported [7].

In the previous work [8] electronic and nuclear stopping powers of a superheavy ion with Z=120 and A=300 at 26 energies ranging from 0.0177 to 0.141 MeV/u in UF_4, He, Mylar and butane have been estimated. Since hot fusion could be used in producing elements with $Z \geq 120$, the energy range has been expanded to 0.20 MeV/u to estimate stopping powers of a heavy ion with Z=120 and A=300 in Al and UO_2 [9]. In this work stopping powers of superheavy ions with Z>120 in Al and those with $Z \geq 120$ in U are estimated at 35 energies ranging from 0.01 to 0.20 MeV/u. The estimation has been evaluated for light ions.

II. ENERGY LOSS OF SUPERHEAVY IONS IN MEDIA

Energy loss of superheavy ions in media arises from their electronic and nuclear stopping powers. The electronic stopping powers were deduced by fitting data from SRIM with a function with six parameters [8] or by fitting them with a following function [9]:

$$(-dE/dx)_e/Z^2 = a_1 + a_2 \exp[-a_3/Z^{2/3}] \quad (1)$$

The nuclear stopping powers of the superheavy ion were deduced with a fifth-order polynomial fit with respect to Z [8, 9]. Electronic stopping power of ^{289}Fl in Mylar at 24.7±4.0 MeV deduced by Eq. (1) was 30.2±2.7 MeV/(mg/cm^2) with its corresponding nuclear stopping powers of 8.3±1.2 MeV/(mg/cm^2) [9]. The resulting total stopping power of 38.5±3.0

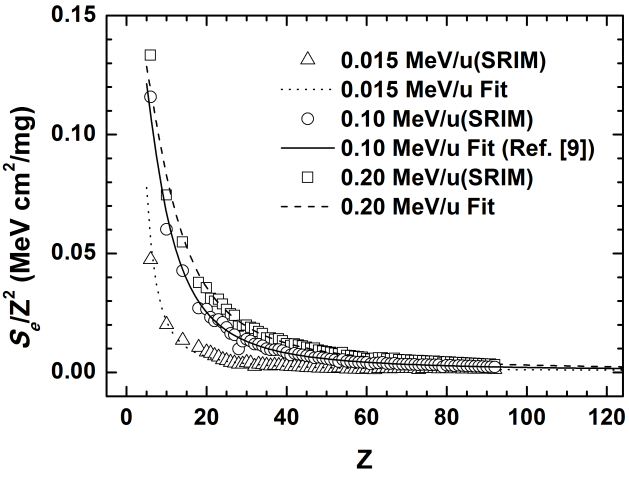

FIG. 1: Electronic stopping powers of the ions in Al divided by Z^2 at 0.015, 0.10 and 0.20 MeV/u. Open symbols are obtained from SRIM [6] and the lines refer to their corresponding fits with Eq. (1).

MeV/(mg/cm^2) agreed quite well with the experimental one of 34.9±15.4 MeV/(mg/cm^2), implying that this estimation is applicable to superheavy ions with Z=120 or even higher.

A. Stopping powers of superheavy ions with Z>120 and A=300 in Al

Electronic and nuclear stopping powers of 77 ions ranging from C to U in Al at 35 energies have been obtained from SRIM [6]. Their atomic numbers are 6, 10, 14, 18, 20, 21, 22,..., 91, and 92. Their 35 energies range from 0.01 to 0.20 MeV/u. The electronic and nuclear stopping powers at each energy have been used to extrapolate the corresponding stopping powers of heavy ions with Z=120 and A=300 with Eq. (1) and the fifth-order polynomial fit, respectively [9] and to further extrapolate those of heavy ions with Z=122 and 124 and A=300. The fits and the resulting variations at 0.015, 0.10 and 0.20 MeV/u are shown in Figs. 1 and 2, respectively. They show that the fits work well with most of the ions except five ions with variations larger than 35 % at 0.015 MeV/u and three ions with variations larger than 15 % at 0.10 MeV/u. The ions at 0.015 MeV/u are Ge with 35 %, Cs with 35 %, Ce with 36 %, Pr with 37 % and Sm with 46 % variation, while those at 0.10 MeV/u are Ni with 48 %, Pm with 19 % and Au with 25 % variation [9].

Electronic stopping powers of ^{16}O and ^{19}F ions in Al deduced by Eq. (1) have been com-

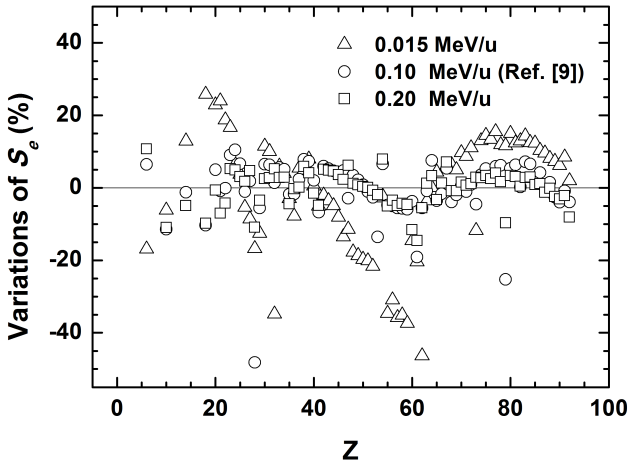

FIG. 2: Variations of the fits in Fig. 1.

pared with the corresponding experimental data [10]. The results are shown in Table I and Figs. 3 and 4. The estimated stopping powers of the ^{16}O ion agree with the corresponding experimental values within less than 5 % variation above 2 MeV, 6-14 % between 0.81 and 1.87 MeV (0.05 and 0.12 MeV/u) and 17-19 % below 0.8 MeV, while the SRIM data agree with them with 5-7 % variation between 1.11 and 3.14 MeV (0.07 and 0.20 MeV/u) and less than 5 % below 1 MeV. The estimated stopping powers of the ^{19}F ion agree with the corresponding experimental values within 3-9 % variation above 1.9 MeV, 13-25 % between 0.58 and 1.75 MeV (0.03 and 0.09 MeV/u), and 31-47 % below 0.5 MeV, while the SRIM data agree with them with 6-10 % variation above 1 MeV, 15-33 % between 0.58 and 0.88 MeV (0.03 and 0.05 MeV/u) and 33-52 % below 0.5 MeV. The estimation works even better for the ^{16}O and ^{19}F ions above 0.12 MeV/u than the SRIM data.

Nuclear stopping powers of the superheavy ions with Z=122 and 124 and A=300 have been extrapolated by a fifth-order polynomial fit [8, 9]. The fits and the resulting variations at 0.015, 0.10 and 0.20 MeV/u are shown in Figs. 5 and 6, respectively. The fits work well with all the ions within 0.1 % variation except four light ions, C with 1.2-2.1 % , Ne with 0.4-0.8 %, Si with 0.2-0.5 % and Ar with 0.2 % variation. The results are listed in Table II and the total stopping powers are shown in Fig. 7. The electronic and nuclear stopping powers for the ^{300}122 ion at 0.20 MeV/u are 36.1 and 4.2 MeV/(mg/cm^2), respectively, while those at 0.015 MeV/u are 14.4 and 15.6 MeV/(mg/cm^2). The corresponding stopping powers of the ^{300}124 ion at 0.20 MeV/u are 36.5 and 4.3 MeV/(mg/cm^2), while those at

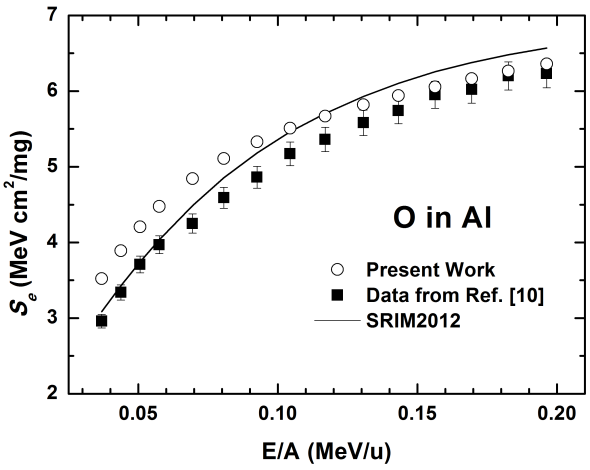

FIG. 3: Electronic stopping powers of ^{16}O in Al.

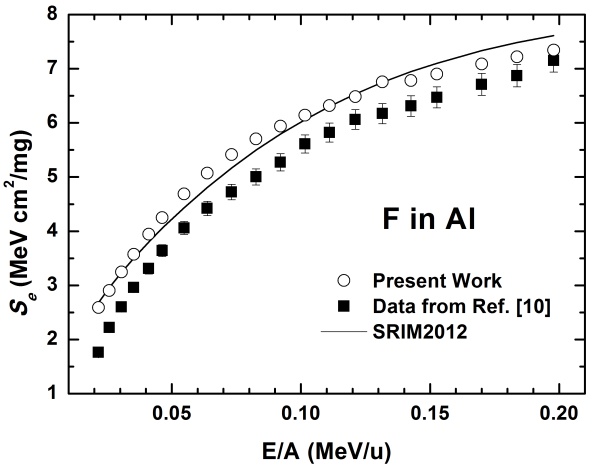

FIG. 4: Electronic stopping powers of ^{16}F in Al.

0.015 MeV/u are 14.7 and 15.8 MeV/(mg/cm^2). The electronic stopping powers are smaller than their corresponding nuclear ones at $E \geq 0.017$ MeV/u. Fig. 7 shows that total stopping powers of the ^{300}122 and ^{300}124 ions tend to decrease slightly until 0.043 MeV/u, that is a little higher than 0.04 MeV/u in the ^{300}120 ion [9], and then increase smoothly as the energy increases.

TABLE I: Electronic stopping powers of ^{16}O and ^{19}F ions in Al

^{16}O				^{19}F			
E	S_e	S_e^a	S_e^b	E	S_e	S_e^a	S_e^b
MeV	MeV/(mg/cm^2)			MeV	MeV/(mg/cm^2)		
0.59	3.52	2.96	3.09	0.41	2.59	1.76	2.68
0.70	3.89	3.34	3.43	0.49	2.90	2.22	2.96
0.81	4.21	3.71	3.74	0.58	3.25	2.60	3.24
0.92	4.48	3.97	4.04	0.67	3.57	2.96	3.50
1.11	4.84	4.25	4.49	0.78	3.94	3.31	3.80
1.29	5.11	4.59	4.85	0.88	4.25	3.64	4.05
1.48	5.33	4.86	5.18	1.04	4.69	4.06	4.43
1.67	5.51	5.17	5.46	1.21	5.07	4.42	4.81
1.87	5.67	5.36	5.71	1.39	5.41	4.72	5.17
2.09	5.82	5.58	5.93	1.57	5.70	5.00	5.49
2.29	5.94	5.74	6.10	1.75	5.94	5.27	5.79
2.50	6.06	5.95	6.26	1.93	6.14	5.61	6.06
2.71	6.16	6.02	6.38	2.11	6.32	5.82	6.30
2.92	6.26	6.20	6.48	2.30	6.48	6.06	6.53
3.14	6.36	6.23	6.57	2.50	6.76	6.17	6.75
				2.71	6.78	6.31	6.94
				2.90	6.90	6.47	7.10
				3.23	7.09	6.71	7.33
				3.49	7.22	6.87	7.48
				3.76	7.34	7.15	7.61

Values of S_e^a were taken from Ref. [10] and those of S_e^b obtained from SRIM [6].

B. Stopping powers of superheavy ions with $Z \geq 120$ and A=300 in U

Electronic and nuclear stopping powers of superheavy ions with Z=120, 122 and 124 and A=300 in U have been estimated similarly as stated in the previous section. The fits for the electronic stopping powers and the resulting variations at 0.015, 0.10 and 0.20 MeV/u are

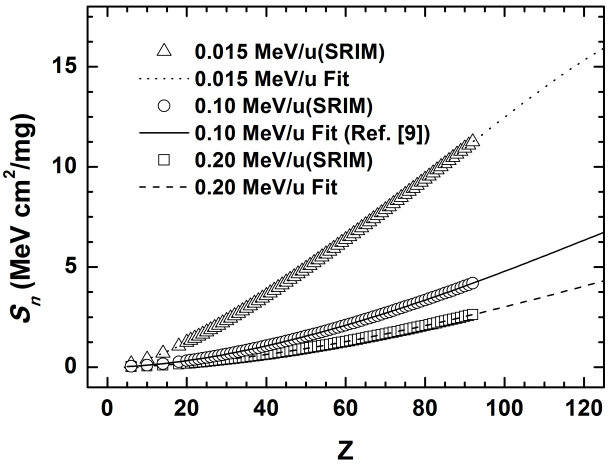

FIG. 5: Fifth-order polynomial fits for nuclear stopping powers of the ions in Al at 0.015, 0.10 and 0.20 MeV/u. Open symbols are obtained from SRIM [6] and the lines refer to their corresponding fits.

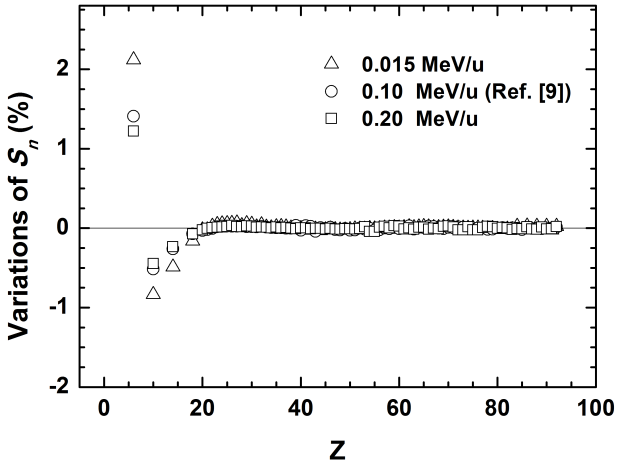

FIG. 6: Variations of the fits in Fig. 5.

shown in Figs. 8 and 9, respectively. They show that the fits work well with most of the ions except six ions with variations larger than 30 % at 0.015 MeV/u and three ions with variations larger than 14 % at 0.10 MeV/u. The ions at 0.015 MeV/u are Ge with 35 %, Cs with 35 %, Ba with 31 %, La with 36 %, Pr with 37 % and Sm with 46 % variation, while those at 0.10 MeV/u are Ni with 48 %, Pm with 19 % and Au with 25 % variation. Electronic stopping powers of the Lr (Z=103) ion estimated at 0.015, 0.10 and 0.20 MeV/u are 2.0, 5.9

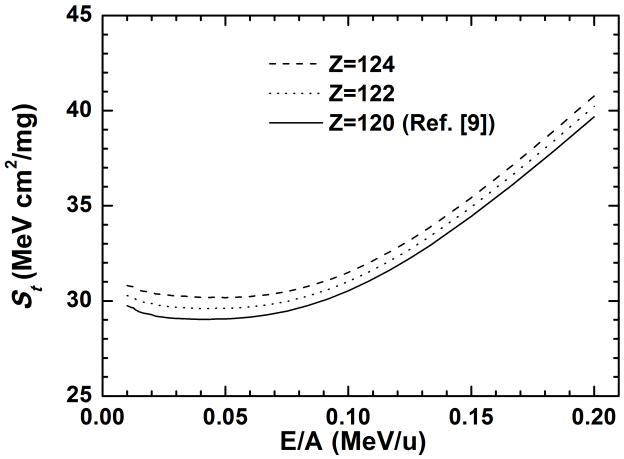

FIG. 7: Total stopping powers of the superheavy ions with Z=122 and 124 and A=300 in Al at 35 energies ranging from 0.01 to 0.20 MeV/u.

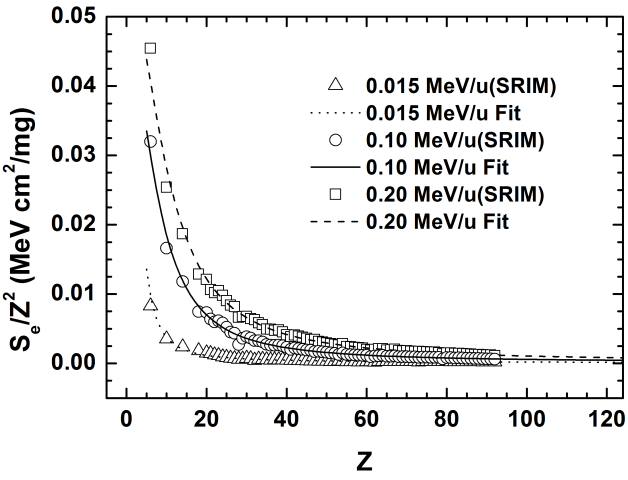

FIG. 8: Electronic stopping powers of the ions in U divided by Z^2 at 0.015, 0.10 and 0.20 MeV/u. Open symbols are obtained from SRIM [6] and the lines refer to their corresponding fits with Eq. (1).

and 10.9 MeV/(mg/cm^2), respectively, while their corresponding values in Northcliffe and Schilling′s tables are 1.3, 4.6 and 8.2 MeV/(mg/cm^2). Their discrepancies are within a 40 % variation above 0.04 MeV/u and increase to more than 60 % variation at the lower energy region.

The fits for the nuclear stopping powers and the resulting variations at 0.015, 0.10 and

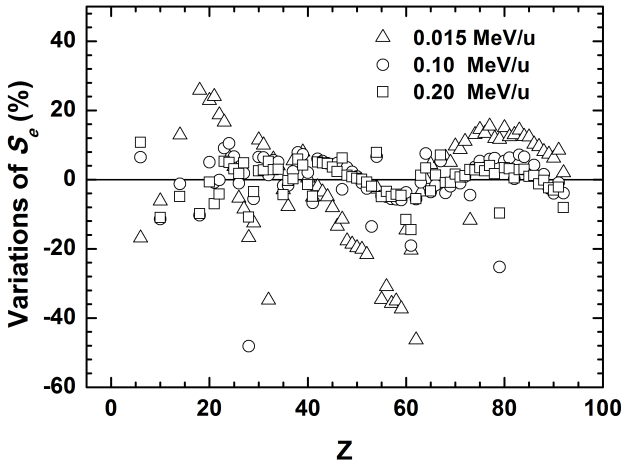

FIG. 9: Variations of the fits in Fig. 8.

0.20 MeV/u are shown in Figs. 10 and 11, respectively. They work well with all the ions within 0.1 % variation except four light ions, C with 1.7-2.4 % , Ne with 0.5-1.0 %, Si with 0.3-0.5 % and Ar with 0.1-0.2 % variation. The results are listed in Table III and the total stopping powers with those of ^{238}U are shown in Fig. 12. The electronic and nuclear stopping powers for the ^{300}120 ion at 0.20 MeV/u are 12.1 and 2.2 MeV/(mg/cm^2), respectively, while those at 0.01 MeV/u are 2.0 and 7.4 MeV/(mg/cm^2). The corresponding stopping powers of the ^{300}122 ion at 0.20 MeV/u are 12.3 and 2.3 MeV/(mg/cm^2), while those at 0.01 MeV/u are 2.1 and 7.5 MeV/(mg/cm^2). The corresponding stopping powers of the ^{300}124 ion at 0.20 MeV/u are 12.4 and 2.3 MeV/(mg/cm^2), while those at 0.01 MeV/u are 2.1 and 7.5 MeV/(mg/cm^2). The total stopping powers decrease slightly until about 0.040 MeV/u for Z=120, 0.043 MeV/u for Z=122 and 0.046 MeV/u for Z=124 ion that are higher than 0.02 MeV/u for the ^{238}U (Z=92) ion and increase smoothly as the energy increases as shown in Al, except a little oscillation below 0.0125 MeV/u.

III. CONCLUSIONS

Electronic and nuclear stopping powers of superheavy ions with Z=122 and 124 and A=300 in Al and Z=120, 122 and 124 and A=300 in U at 35 energies ranging from 0.01 to 0.20 MeV/u have been deduced using the data obtained from SRIM. The total stopping powers of the ^{300}122 and ^{300}124 ions in Al tend to decrease slightly until 0.043 MeV/u, that

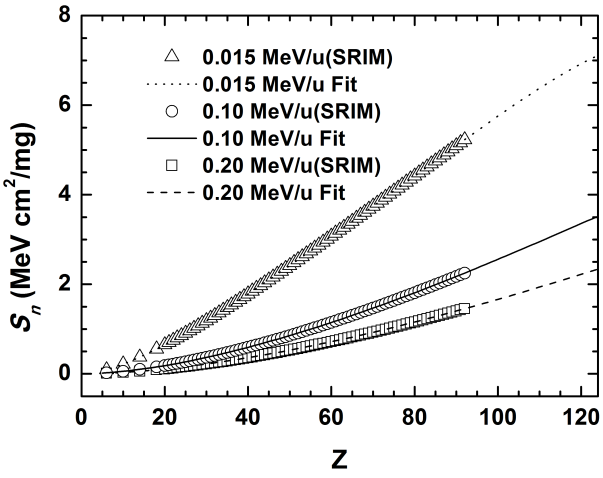

FIG. 10: Fifth-order polynomial fits for nuclear stopping powers of the ions in Al at 0.015, 0.10 and 0.20 MeV/u. Open symbols are obtained from SRIM [6] and the lines refer to their corresponding fits.

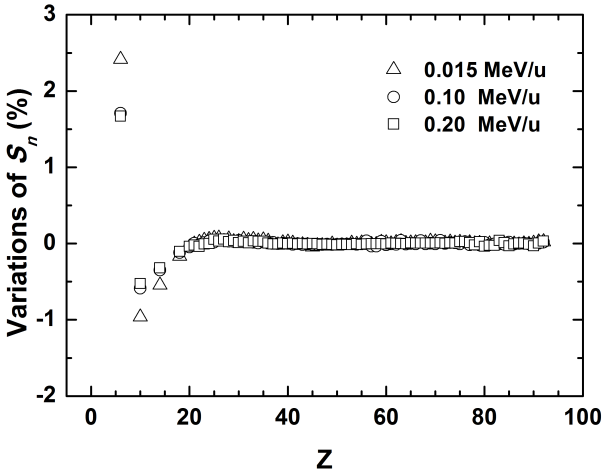

FIG. 11: Variations of the fits in Fig. 10.

is a little higher than 0.04 MeV/u in the ^{300}120 ion, and then increase smoothly as the energy increases. The total stopping powers in U decrease slightly until about 0.040 MeV/u for Z=120, 0.043 MeV/u for Z=122 and 0.046 MeV/u for Z=124 ion that are higher than 0.02 MeV/u for the ^{238}U ion and increase smoothly as the energy increases. Electronic stopping powers of the Lr ion in U estimated at 0.02, 0.10 and 0.20 MeV/u are compared with their corresponding values in Northcliffe and Schilling′s tables. Their discrepancies are within a

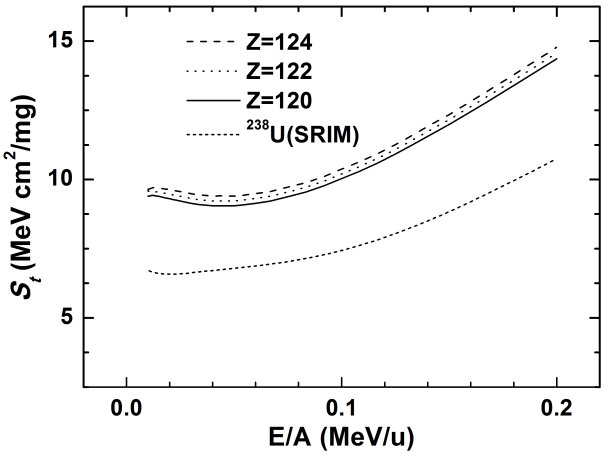

FIG. 12: Total stopping powers of the superheavy ions with Z=120, 122 and 124 and A=300 in U at the same energies as in Fig. 7.

40% variation above 0.04 MeV/u and tend to increase at the lower energy region.

The estimated electronic stopping powers of ^{16}O and ^{19}F ions agreed well with the experimental values above 0.10 MeV/u, while there were larger deviations near 0.01 MeV/u. This implies that this estimation would be applicable to superheavy ions as well as light ions above 0.10 MeV/u.

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TABLE II: Stopping powers of superheavy ions with Z=120, 122, and 124 and A=300 in Al

	Z=120[a]		Z=122		Z=124	
E	S_e	S_n	S_e	S_n	S_e	S_n
MeV/u	MeV/(mg/cm^2)					
0.010	12.745	17.002	13.045	17.237	13.348	17.457
0.011	12.987	16.714	13.290	16.955	13.597	17.183
0.012	13.221	16.436	13.527	16.683	13.837	16.918
0.013	13.448	16.182	13.758	16.437	14.070	16.681
0.013	13.669	15.872	13.981	16.123	14.296	16.362
0.015	14.093	15.326	14.411	15.575	14.733	15.813
0.017	14.498	14.858	14.822	15.112	15.149	15.357
0.018	14.886	14.433	15.214	14.692	15.546	14.943
0.020	15.253	14.019	15.586	14.279	15.922	14.533
0.022	15.584	13.605	15.920	13.861	16.259	14.111
0.023	15.942	13.225	16.283	13.479	16.627	13.727
0.027	16.564	12.547	16.910	12.797	17.260	13.042
0.030	17.130	11.940	17.481	12.184	17.835	12.424
0.033	17.647	11.411	18.000	11.651	18.356	11.889
0.037	18.119	10.914	18.474	11.147	18.832	11.377
0.040	18.552	10.471	18.907	10.698	19.265	10.922
0.043	18.956	10.070	19.310	10.291	19.668	10.510
0.047	19.331	9.719	19.685	9.938	20.041	10.155
0.050	19.682	9.365	20.033	9.575	20.387	9.784
0.053	20.015	9.054	20.364	9.260	20.716	9.464
0.057	20.334	8.771	20.681	8.973	21.030	9.174
0.060	20.640	8.505	20.984	8.702	21.331	8.899
0.067	21.232	8.026	21.571	8.215	21.913	8.404
0.075	21.954	7.503	22.287	7.681	22.622	7.859
0.083	22.677	7.072	23.006	7.245	23.336	7.418
0.092	23.420	6.680	23.746	6.844	24.074	7.009
0.100	24.195	6.337	24.520	6.495	24.847	6.652
0.108	25.002	6.038	25.328	6.190	25.656	6.342
0.117	25.845	5.762	26.175	5.908	26.506	6.054
0.125	26.723	5.511	27.058	5.651	27.395	5.790
0.133	27.633	5.294	27.975	5.429	28.319	5.565
0.150	29.537	4.907	29.897	5.034	30.260	5.162
0.167	31.518	4.580	31.903	4.700	32.290	4.821
0.183	33.561	4.295	33.974	4.409	34.390	4.523
0.200	35.630	4.045	36.075	4.151	36.522	4.259

[a]The data are taken from Ref. [9].

TABLE III: Stopping powers of superheavy ions with Z=120, 122, and 124 and A=300 in U

	Z=120		Z=122		Z=124	
E	S_e	S_n	S_e	S_n	S_e	S_n
MeV/u			MeV/(mg/cm^2)			
0.010	2.041	7.363	2.089	7.512	2.138	7.512
0.011	2.119	7.284	2.168	7.364	2.218	7.437
0.012	2.193	7.231	2.244	7.318	2.295	7.398
0.013	2.265	7.158	2.317	7.248	2.369	7.331
0.013	2.333	7.076	2.386	7.168	2.440	7.252
0.015	2.463	6.926	2.519	7.022	2.575	7.111
0.017	2.586	6.776	2.643	6.874	2.702	6.966
0.018	2.700	6.632	2.760	6.733	2.820	6.829
0.020	2.810	6.498	2.871	6.602	2.933	6.701
0.022	2.914	6.359	2.977	6.463	3.041	6.563
0.023	3.014	6.234	3.079	6.340	3.144	6.442
0.027	3.205	5.991	3.272	6.098	3.339	6.202
0.030	3.384	5.754	3.453	5.859	3.523	5.962
0.033	3.556	5.543	3.627	5.647	3.699	5.748
0.037	3.721	5.352	3.794	5.455	3.867	5.557
0.040	3.882	5.168	3.956	5.269	4.031	5.368
0.043	4.032	5.019	4.107	5.122	4.183	5.223
0.047	4.194	4.858	4.270	4.958	4.348	5.057
0.050	4.346	4.705	4.424	4.802	4.502	4.897
0.053	4.498	4.575	4.576	4.670	4.655	4.765
0.057	4.648	4.459	4.728	4.555	4.808	4.649
0.060	4.799	4.343	4.879	4.437	4.959	4.530
0.067	5.100	4.121	5.181	4.211	5.263	4.299
0.075	5.480	3.896	5.563	3.985	5.647	4.072
0.083	5.868	3.678	5.953	3.761	6.039	3.843
0.092	6.267	3.502	6.354	3.582	6.442	3.662
0.100	6.677	3.356	6.766	3.436	6.857	3.517
0.108	7.097	3.202	7.190	3.279	7.283	3.356
0.117	7.529	3.064	7.625	3.137	7.722	3.210
0.125	7.971	2.945	8.071	3.016	8.171	3.087
0.133	8.421	2.847	8.525	2.918	8.630	2.989
0.150	9.339	2.648	9.453	2.714	9.568	2.780
0.167	10.273	2.487	10.399	2.550	10.525	2.613
0.183	11.21 0	2.343	11.348	2.403	11.487	2.462
0.200	12.140	2.222	12.292	2.279	12.444	2.337